

METHANE PRODUCTION BY ANAEROBIC DIGESTION OF WATER HYACINTH (EICHHORNIA CRASSIPES)

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INTRODUCTION

Water hyacinth (Eichhornia crassipes) is an aquatic biomass species that exhibits prolific growth in many parts of the world (1). It has been suggested as a strong candidate for production of methane because of high biomass yield potential (2). Several studies have been carried out which establish that methane can be produced from water hyacinth under anaerobic digestion conditions (3-6). Both batch and semicontinuous digestion experiments were performed. The highest apparent gas yields reported were obtained in the batch mode of operation over long detention times (4), but the yields were based on wet hyacinth containing unspecified amounts of water and ash. Some of the data in the literature on gas yield and production rate are difficult to interpret because they are experimentally observed values and are not reduced to standard conditions. The energy recovery efficiencies in the product gas are also not available because the energy contents of the feed were not determined. The work described in this paper was initiated to develop more quantitative data in terms of the physical and chemical characteristics of water hyacinth.

MATERIALS AND METHODS

Digesters

The digestion runs were carried out in the semicontinuous mode in cylindrical, complete-mix, 7- ℓ digesters (7). The culture volume for all experiments was 5 ℓ , and the internal diameter of the digesters was 19 cm. Continuous mixing at 130 rpm was provided with two 7.6-cm propeller-type impellers located 7.6 and 15.2 cm from the digester bottom on a central shaft.

Analytical Techniques

Most analyses were performed in duplicate; several were performed in triplicate or higher multiples. The procedures were either ASTM, Standard Methods, special techniques as reported previously (8), or other techniques as indicated by footnotes in the tables.

Data Reduction

Gas yield, methane yield, volatile solids reduction, and energy recovery efficiency were calculated by the methods described previously (8). All gas data reported are converted to 60°F and 30 in. of mercury on a dry basis.

Digester Feeds

One-half to one ton samples of water hyacinth were harvested for this work.

Water hyacinth was harvested from an experimental sewage-treatment lagoon of NASA's National Space Technology Laboratory in Bay St. Louis, Mississippi. Whole adult and young plants were collected and fed directly to an agricultural chopper that provided particles about 3 in. or smaller in size. The chopped hyacinth was placed in polyethylene-lined fiber drums, frozen, shipped by refrigerated truck to IGT, stored at -10°F, ground in a laboratory grinder, mixed in a double-ribbon blender to ensure homogeneity, placed in one-half gallon cartons, and stored at about -20°F.

During one of the harvests (June 3, 1977), small samples of whole plants were also collected, in addition to the chopped plants, and shipped separately to IGT overnight in sealed

bottles without freezing for moisture, volatile matter, and ash analyses. The results are shown in Table 1 along with the corresponding analyses for the hyacinth treated as described above.

Whole water hyacinth plants were collected from a 0.25-ac freshwater pond in the Lee County Hyacinth Control District, Fort Myers, Florida. This pond is located northeast of Fort Meyers in an unincorporated area known as Buckingham and receives both surface run-off and ground water. The pond is stagnant, has no outlet, is about 3 m deep, and has a mucky bottom. The whole plants were shipped by unrefrigerated truck to IGT in polyethylene-lined fiber drums. After arrival at IGT, the water hyacinth was treated in the same manner as the Mississippi shipments.

Grinding of the water hyacinth in the laboratory was achieved with an Urschel Laboratory Grinder (Comitrol 3600) equipped with 0.030-in. cutting head. A typical particle size analysis is shown in Table 2, and the effects of storage time on the moisture, volatile matter, and ash contents are shown in Table 3.

The characteristics of the particular lots of hyacinth used to make the feed slurries for the digestion runs reported in this paper are summarized in Table 4. Feed slurries were prepared fresh daily by blending the required amounts of ground hyacinth and demineralized water. The properties of the slurries are compared in Table 5. The pH of the digester contents was maintained in the desired range by adding a predetermined amount of caustic solution to the feed slurry before dilution to the required amount with water. When added nutrient solutions were used, the compositions of which are shown in Table 6, preselected amounts were also blended with the feed slurries before dilution to the final feed volume.

Inoculum, Start-Up and Operation

The inoculum for the initial replicate digestion runs (Runs 1M-B and 2M-B) was developed by accumulating daily effluents from existing laboratory digesters operating on giant brown kelp and primary-activated sewage sludge as described previously (7). These digesters were then operated in the semicontinuous mode with initial mixed inoculum volumes of 2.5% and a daily feeding and wasting schedule aimed at increasing the working volume to 5% over an 8-day period, after which a transition period was incurred to change the feed to 100% hyacinth (7). The total time required from start-up to conversion to hyacinth feeds was 42 days. A second transition period was then used to adjust the operating conditions to a loading of 0.1 lb volatile solids (VS)/ft³-day and a detention time of 12 days; this required 21 days (7). Digestion was then continued at the target operating conditions with hyacinth feed only.

The experimental results obtained at steady state with Runs 1M-B, 2M-B and subsequent runs are shown in Table 7. Steady-state digestion was defined in this work as operation without significant change in gas production rate, gas composition, and effluent characteristics. Usually, operation for two or three detention times established steady-state digestion.

Mesophilic Runs 1M-4, 1M-7, 1M-8, and 1M-9 were each successively derived starting from the initial Run 1M-B. Run 1M-4 shows the effects of added nitrogen as an ammonium chloride solution. Run 1M-7 shows the effects of terminating caustic additions to maintain pH. Run 1M-8 was developed by replacing the Mississippi hyacinth in the feed slurry with Florida hyacinth. Run 1M-9 is a continuation of Run 1M-8 except caustic additions were made to control pH. Run 2M-3 was derived from Run 2M-B and was carried out with additions of the mixed nutrient solution.

Thermophilic Run 1T-5 was developed from the effluents of mesophilic Runs 1M-B and 2M-B. Successively, the effluents were collected and used as inoculum (16 days); the digester was operated at the conditions of Runs 1M-B and 2M-B to stabilize the new digester (16 days); the temperature was increased to 55°C and the digester was kept in the batch mode (14 days); the semicontinuous mode of operation was started with gradual change of the detention time from 106 days to 16.7 days and of the loading from 0.01 to 0.15 lb VS/ft³-day

(27 days); and Run 1T-5 was continued. Runs 1T-8, 1T-10, and 1T-11 were each successively derived starting from Run 1T-5. Runs 1T-8 and 1T-10 were operated at higher loading rates and lower detention times than Run 1T-5; ammonium chloride solution was added to each of these runs. Run 1T-11 is identical to Run 1T-10 except that nitrogen additions were terminated.

Dewatering Tests

Gravity sedimentation tests were conducted by a modification of the AEEP Method (9) in which a 400-ml sample of the effluent was examined in a 1- ℓ graduated cylinder giving a fluid depth of 140 mm (7). Vacuum filtration tests were conducted by a modification of the AEEP Method (10) in which a 417-ml sample of effluent was filtered through a monofilament filter cloth (7).

DISCUSSION

Feed Properties

The roots of water hyacinth had higher ash and lower volatile matter contents than other parts of the plant as shown by the data in Table 1. Harvesting and storage times as well as the source of the plant seemed to have little effect on the moisture, volatile matter, and ash contents of the plants as illustrated by the data in Table 3. Samples harvested many months apart in Mississippi had essentially the same volatile matter and ash contents. The sample harvested in Florida had slightly higher volatile matter and slightly lower ash contents than the Mississippi samples, but this might be expected in view of the different growth media from which the hyacinth harvests were taken. The Mississippi hyacinth was grown in a sewage-fed lagoon, and hyacinth is known to take up heavy metals from such media (1).

The data on the chemical and physical properties of the Mississippi and Florida hyacinths used in this work (Table 4) indicate some interesting differences. The C/N and C/P weight ratios are each lower for the Mississippi hyacinth than the Florida hyacinth, but both sets of ratios appear to be somewhat high when compared with the corresponding ratios supplied by suitable feeds for anaerobic digestion such as giant brown kelp and sewage sludge (7). Although analytical data for the organic components in Florida hyacinth were not obtained, the relatively high hemicellulose content of the Mississippi hyacinth indicates potentially good digestibility (7). Interestingly, the theoretical methane yield derived from the empirical formula and stoichiometric conversion (7) of the Mississippi hyacinth has a maximum value about 14% higher than that of the Florida hyacinth.

Comparison of the feed slurries (Table 5) also reveals some interesting differences. The slurry made with the Mississippi hyacinth had a lower pH and buffering capacity than the Florida hyacinth slurry and therefore needed more caustic for pH control. However, the ammonia nitrogen concentrations in each slurry appeared too low for good digestion when compared to the beneficial range for sewage digestion (11). Concentrations of calcium, potassium, sodium, and magnesium calculated from the data in Table 4 for the feed slurries, assuming each element is totally dissolved, were either in the stimulatory range or less than the inhibitory range (11). Addition of sodium hydroxide for pH control, although increasing the sodium ion concentration several-fold, was still estimated to be insufficient to raise the sodium ion concentration to the inhibitory range. Also, addition of lime for pH control (Run 1M-9) at the level required raised the calcium ion concentration in the feed slurry but not enough to inhibit digestion based on sewage digestion and inhibition by metallic cations (11).

Mesophilic Digestion

Operation of replicate Runs 1M-B and 2M-B on Mississippi hyacinth without added nutrients showed good reproducibility and balanced digestion. Typical operating performance over a period of several detention times is shown in Figure 1. It was found that to maintain pH in the desired range, about 45-50 meq of sodium hydroxide per liter of feed had to be added.

To attempt to increase methane yields, pure and mixed nutrient solution additions were made in Runs 1M-4 and 2M-3, respectively, while controlling pH with added caustic. Little change was observed in digester performance; the gas production rates and yields were about the same as those observed without nutrient additions.

Elimination of both pH control and nutrient additions in Run 1M-7 resulted in small decreases in pH, methane yield, and methane concentration in the product gas, but overall performance in terms of volatile solids reduction and energy recovery efficiency as methane were about the same as those of the runs with pH control and with or without nutrient additions.

Conversion from Mississippi hyacinth to Florida hyacinth in Run 1M-8, which did not incorporate pH control or nutrient additions and which was identical to Run 1M-7 except for the feed source, showed significant reduction in most of the gas production parameters. Gas production rate and yield and methane yield decreased, but digester performance was still balanced as shown by low volatile acids in the digester effluent and the methane concentration in the product gas. From the elemental analyses and the theoretical methane yields (Table 4), the methane yield for Run 1M-8 would be expected to be about 14% less than that of Run 1M-7; it decreased by about 41%. Prolonged operation of Run 1M-8 for over six detention times did not result in any improvement; the run exhibited steady-state performance with no change in methane yield or gas production rate. Use of pH control (Run 1M-9) and continued operation reduced the methane yield even further. It was concluded from these experiments that the Florida hyacinth sample contained unknown inhibitors or that the Mississippi water hyacinth contained unknown stimulatory components. The latter possibility was considered more likely because the Mississippi hyacinth was grown in a sewage-fed lagoon, and it is well established that normal sewage has good digestion characteristics (11). Also, it is known that water hyacinth when grown in laboratory media enriched with nickel and cadmium, components often found in sewage, incorporates these metals and shows good digestion characteristics (4).

Thermophilic Digestion

Digestion of Mississippi water hyacinth was carried out at 55°C with and without nitrogen supplementation. Balanced digestion was achieved with all four runs, Runs 1T-5, 1T-8, 1T-10, and 1T-11. The gas production rate increased with decreases in detention time and increases in loading rate as expected. Also, as expected, the gas production rate at 55°C was higher than that at 35°C, and again there was no apparent benefit of nitrogen additions. The methane yield ranged from 1.95 to 2.63 SCF/lb VS added over the detention time range studied, 6 to 16.7 days. At the same 12-day detention times, the methane yield at 55°C, 2.42 SCF/lb VS added (Run 1T-8), was lower than those observed for all of the mesophilic runs at 35°C with Mississippi hyacinth. However, comparison of the specific methane production rates [methane production rate ÷ (loading × detention time)] in Table 7 shows that at the highest loading and shortest detention time studied in this work (Runs 1T-10 and 1T-11), the rate of methane production per pound of volatile solids added is higher at 55°C than at 35°C even though the methane yields are lower.

Carbon and Energy Balances

The difficulty of calculating carbon and energy balances for digestion experiments in which additions of alkali and nutrients are made has been discussed before (7). These additives contribute to ash weights. The two methods used to circumvent this problem in previous work (7) were also used in this paper. They are described in the footnotes to Table 8, which presents sample calculations by each method for Runs 1M-B, 2M-E, and 1M-9. Run 1M-9 exhibited the largest deviation from the theoretical carbon and energy balances; both balances were quite low and only accounted for 81 to 87% of the feed carbon and 86 to 92% of the feed energy. The major reason for this is probably the deviation in the experimental gas production measurements. Run 1M-9 had the largest coefficients of variation of all the runs for both gas production rate and yield (Table 7).

Properties of Effluent and Digested Solids

A comparison of fresh feed slurries and effluents from Runs 1M-B, 1M-4, and 1M-8 is presented in Table 9. The addition of sodium hydroxide for pH control in Run 1M-B had the expected effects on total and bicarbonate alkalinities, pH, and conductivity. The effluent from Run 1M-4, which was subjected to both caustic and nitrogen additions, showed the same trends except that the ammonia nitrogen concentration also increased. Run 1M-8, which had neither caustic or nitrogen additions, showed a significant increase in alkalinities and a major reduction in volatile acids. The volatile acids present in the fresh feed slurry were expected to undergo a large decrease on balanced digestion. However, the conversion of non-ammonia nitrogen in the feed to ammonia nitrogen in the effluent is not apparent in these runs in contrast to the usual increase observed on digestion (7). Also, because of the moderate to low volatile solids reductions in these experiments, the chemical oxygen demands of the digester effluents are relatively high.

A few experiments were carried out to examine the gravity sedimentation and filtration characteristics of digester effluent from Run 1M-B. The sedimentation results for unconditioned and conditioned effluent are shown in Figure 2. The settling characteristics were poor and the conditioning treatment improved settling only slightly. A more detailed study is necessary to optimize the conditioning method. Similarly, the filtration characteristics of the conditioned and unconditioned effluent shown in Table 10 were poor.

The properties of the dry feeds and digested solids from Runs 1M-B, 2M-B, and 1M-9 are listed in Table 11. Carbon content, volatile matter, and heating value of the total digested solids decreased on digestion as expected while ash content increased. The heating value per pound of contained carbon remained reasonably constant from dry feed to dry digested solids, but there appeared to be a significant reduction in the heating value of the volatile matter in the Florida hyacinth residual solids, while the heating value of the Mississippi hyacinth residual solids remained about the same as the feed. As indicated in previous work (7), this may be due to the difference in degradabilities of different organic components.

Thermodynamic Estimates

The maximum theoretical methane yields uncorrected for cellular biomass production for the Mississippi and Florida water hyacinth samples used for the digestion runs were estimated to be 9.36 and 8.20 SCF/lb VS reacted (Table 4). Assuming that 7% of the protein and 20% of the carbohydrate is converted to cells on one pass through the digester, the maximum theoretical yield of methane for Mississippi hyacinth is given by (7):

$$(1 \text{ lb VS added} - 0.195 \text{ lb VS to cells}) \left(9.36 \frac{\text{SCF CH}_4}{\text{lb VS reacted}} \right) = 7.53 \frac{\text{SCF CH}_4}{\text{lb VS-pass}}$$

If the same conversion factor is assumed to be valid for the Florida hyacinth sample, the corresponding yield is 6.60 SCF CH₄/lb VS-pass. The highest experimental methane yields observed for the Mississippi and Florida hyacinth samples used in this work are 3.13 and 1.66 SCF/lb VS added, or about 42% and 25% of these theoretical values.

Comparison With Other Substrates

The methane yields, volatile solids reductions, and energy recovery efficiencies as methane in the product gas from experiments carried out under similar high-rate conditions with other substrates are summarized in Table 12 (7) along with the results from Run 2M-B. The relatively narrow span of the yields and efficiencies when considered together suggest that standard high-rate conditions in the conventional range tend to afford about the same digestion performance with degradable substrates. The basic organic components groups in these substrates are similar. Usually, the largest fraction consists of mono and polysaccharides and the smallest fraction is lignin, if present at all. The protein content is usually intermediate in concentration. Experimental data indicate that the hemicelluloses are generally more degradable than the celluloses on digestion (7), and that the celluloses and protein fraction are lower in degradability than the monosaccharides (12). Thus, feeds

high in hemicelluloses and monosaccharides should exhibit high gasification rates, but the actual concentrations of these components in the feeds might be expected to govern gas yields. Further improvements in yields and energy recovery efficiencies are therefore more likely through post- or pre-treating procedures that increase the degradabilities of the resistant organic components in biomass, or through longer residence times. For example, about 90% of the monosaccharide glucose was converted to product gas on anaerobic digestion at an overall residence time of about 4.5 days in a two-phase system (13), while long-term digestion of cellulose indicates an ultimate anaerobic biodegradability of about 75% (14). A mixed biomass-waste feed containing water hyacinth has been estimated to have an ultimate biodegradability of 66% (15).

CONCLUSIONS

Water hyacinth under conventional high-rate digestion conditions exhibited higher methane yields and energy recovery efficiencies when grown in sewage-fed lagoons as compared to the corresponding values obtained with water hyacinth grown in a fresh-water pond. Mesophilic digestion provided the highest feed energy recovered in the product gas as methane while thermophilic digestion, when operated at sufficiently high loading rates and reduced detention times, gave the highest specific methane production rates. Methane yields, volatile solids reduction, and energy recovery as methane for the sewage-grown water hyacinth were in the same range as those observed for other biomass substrates when digested under similar conditions.

ACKNOWLEDGMENT

This research was supported by United Gas Pipe Line Company, Houston, Texas. The project was performed under the management of UGPL and is currently managed by the Gas Research Institute. The assistance of Dr. B. C. Wolverton of NASA and Mr. E. S. Del Fosse of the Lee County Hyacinth Control District, Fort Myers, Florida in obtaining the hyacinth samples is gratefully appreciated. The authors also wish to thank Dr. Victor Edwards and Mr. Robert Christopher of United for the many valuable discussions and suggestions. We also acknowledge the efforts of Michael Henry, Janet Vorres, Alvin Iverson, Mona Singh, Frank Sedzielarz, Phek Hwee Yen, and Ramanurti Ravichandran in performing the experimental work.

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Table 1. MOISTURE, VOLATILE MATTER, AND ASP CONTENT OF
MISSISSIPPI WATER HYACINTH PLANT PARTS
Harvested 6-3-77

Plant Part	Moisture	Volatile Matter	Ash
	wt %		
Roots	91.2	63.6	36.4
Stem, Stolon	90.4	80.5	19.5
Stem, Subfloat	90.9	81.2	18.8
Stem, Float	91.1	80.5	19.5
Leaf	87.5	82.6	17.4
Average	90.2	77.7	22.3
Whole (Chopped, Frozen, Thawed, Ground) ^a	95.3	77.7	22.4

^a After shipment to laboratory, thawing, and grinding.

Table 2. TYPICAL PARTICLE SIZE ANALYSIS OF GROUND WATER HYACINTH

<u>U. S. Sieve Size, mm</u>	<u>Retained on Sieve, wt %</u>
1.180	0
0.600	12.7
0.297	34.5
0.250	72.7
0.212	78.2
0.180	85.5
0.149	89.1
0.105	94.8
0.063	98.2

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Table 3. EFFECT OF SOURCE, HARVEST TIME, AND STORAGE ON MOISTURE, VOLATILE MATTER, AND ASH CONTENT OF WATER HYACINTH^a

<u>Source</u>	<u>Harvest Date</u>	<u>Storage Time, mth</u>	<u>Moisture</u>	<u>Volatile Matter</u>	<u>Ash</u>
			<u>wt %</u>		
Bay St. Louis, Mississippi	6-3-77	2.5	95.3	77.5	22.5
		2.8	95.3	77.9	22.1
		7.8	95.0	76.9	23.1
	6-21-78	0.2	94.3	76.5	23.5
		2.2	94.3	75.2	24.8
	7-19-78	2.8	94.5	78.8	21.2
Fort Myers, Florida	3-13-78	0.5	94.7	79.9	20.1
		5.0	94.3	80.9	19.1

^a All samples ground with 0.030-in. cutting head of Urschel grinder, homogenized, stored at -20°F, and thawed before analysis in triplicate.

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Table 4. PHYSICAL AND CHEMICAL CHARACTERISTICS OF WHOLE WATER HYACINTH PLANTS AFTER GRINDING

Source	Mississippi	Florida
Harvesting Date	6-3-77	3-13-78
Ultimate Analysis, wt %		
C	41.1	40.3
H	5.29	4.60
N	1.96	1.51
S	0.49	0.41
P	0.46	0.39
Ca	2.15	5.80
Ka	1.85	0.47
Z	1.46	1.00
Mg	0.35	1.40
Proximate Analysis, wt %		
Moisture	95.3	94.5
Volatile Matter ^a	77.7 (77.5)	80.4
Ash ^a	22.4 (22.5)	19.6
Organic Components, wt % of TS		
Crude Protein ^b	12.3	9.4
Cellulose ^a	16.2	—
Hemicellulose ^a	55.5	—
Lignin ^c	6.1 (5.4)	—
High Heating Value		
Btu/dry lb	6,886	6,389
Btu/lb (AMF)	8,862	7,947
Btu/lb C	16,754	15,856
C/N Weight Ratio	21.0	26.7
C/P Weight Ratio	89.3	103
Theoretical Methane Yield, SCF/lb VS reacted ^d	9.36	8.20
Theoretical Gas Composition, mol % CH ₄	56.1	51.8
Theoretical Heat of Reaction, Btu/lb VS reacted	4,606	4,348

^a USDA Agricultural Handbook methods.

^b Kjeldahl N X 6.25.

^c USDA Agricultural Handbook method, figure in parenthesis is by TAPPI method.

^d Based on empirical formulas; yields are not corrected for cellular biomass production.

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Table 5. COMPARISON OF FEED SLURRIES^a

Water Hyacinth Source	Mississippi	Florida
Density, g/ml at 25°C	1.0249	1.0170
Total Solids, wt % of slurry	2.47	2.41
Volatile Matter, wt % of slurry	1.92	1.92
Total Alkalinity, mg/l as CaCO ₃	425	1,463
pH	5.01	6.10
Bicarbonate Alkalinity, mg/l as CaCO ₃	302	556
Conductivity, umho/cm	3,500	2,100
Volatile Acids, mg/l		
Acetic	50	747
Propionic	102	323
Butyric	47	63
Isobutyric	19	9
Valeric	0	11
Isovaleric	0	11
Total as Acetic	173	1,065
Chemical Oxygen Demand, mg/l	15,860	17,479
Ammonia N, mg/l as N	28.0	9.4

^a Formulated for loading of 0.1 lb VS/ft³-day, 12-day detention time, 5-l culture volume.

Table 6. COMPOSITION OF NUTRIENT SOLUTION

Component	Mixed Nutrient Formulation, g/l	Ammonium Chloride Solution, g/l
NH ₄ Cl	30.0	120.0
NaH ₂ PO ₄	20.0	—
KI	2.0	—
FeCl ₃	2.0	—
MgCl ₂	0.25	—
CoCl ₂	0.25	—
CuCl ₂	0.10	—
NaHCO ₃	0.10	—
CuCl ₂	0.10	—
MnCl ₂	0.10	—
N Concentration, mg/ml	7.85	31.42
P Concentration, mg/ml	0.26	—

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Table 7. SUMMARY OF SELECTED STEADY-STATE DIGESTION DATA

Run	1M-B	2M-B	1M-4	2M-3	1M-7	1M-8	1M-9	1T-5	1T-8	1T-10	1T-11
Feed Source	Miss.	Miss.	Miss.	Miss.	Miss.	Fla.	Fla.	Miss.	Miss.	Miss.	Miss.
<u>Operating Condition</u>											
Temperature, °C	35	35	35	35	35	35	35	55	55	55	55
pH ^b	7.05	7.05	7.02	6.99	6.72	6.57	6.87	7.08	7.00	6.82	6.80
Caustic Dosage, meq/l feed	49	45	47	50	0	0	31	21	17	4	5
Loading Rate, lb VS/ft ³ -day	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.15	0.21	0.30	0.30
Detention Time, day	12	12	12	12	12	12	12	16.7	12	6	6
Total Solids in Feed Slurry, wt %	2.47	2.47	2.47	2.47	2.47	2.41	2.41	3.70	5.19	7.41	7.41
Volatile Solids in Feed Slurry, wt %	1.92	1.92	1.92	1.92	1.92	1.92	1.92	2.87	4.03	5.76	5.76
Nutrients Added ^b	0	0	N	MN	0	0	0	0	N	N	0
C/N Ratio in Feed Slurry	21.0	21.0	8.2	8.2	21.0	26.7	26.7	21.0	11.8	15.1	21.0
C/P Ratio in Feed Slurry	89.3	89.3	89.3	73.2	89.3	103	103	89.3	89.3	89.3	89.3
Detention Times Operated	5.1	5.1	2.8	2.8	2.7	6.6	3.5	1.0	1.4	3.0	1.0
<u>Gas Production^c</u>											
Gas Production Rate, vol/vol-day	0.480(13)	0.497(10)	0.477(6)	0.483(7)	0.488(15)	0.268(13)	0.179(21)	0.688(10)	0.865(11)	1.062(6)	1.026(6)
Gas Yield, SCF/lb VS added	4.81(13)	4.98(10)	4.76(6)	4.82(8)	4.88(15)	2.69(12)	1.79(21)	4.58(8)	4.11(10)	3.55(5)	3.41(8)
Methane Concentration, mol %	64.0	62.8	62.3	60.6	57.4	61.8	66.2	57.5	58.7	57.9	57.3
Methane Yield, SCF/lb VS added	3.08	3.13	2.97	2.92	2.80	1.66	1.19	2.63	2.42	2.06	1.95
Specific Methane Production Rate, SCF/lb VS added-day	0.26	0.26	0.25	0.24	0.23	0.14	0.10	0.16	0.20	0.34	0.33
<u>Efficiencies</u>											
Volatile Solids Reduction, %	28.8	29.8	28.5	28.9	29.2	17.0	11.3	27.4	24.6	21.3	20.4
Feed Energy Recovered as Methane, %	35.2	35.7	33.9	33.3	32.0	21.1	15.2	30.0	27.6	23.5	22.3
Effluent Volatile Acids, mg/l as HOAc	27	26	26	51	9	5	63	7	10	21	16

^a pH maintained as indicated by addition of sodium hydroxide solution, except for Run 1M-9 where lime was used. No caustic additions were made for Runs 1M-7 and 1M-8.

^b "0" denotes no nutrients added to feed slurry. "MN" denotes mixed nutrient solution added to feed slurry. "N" denotes ammonium chloride solution added to feed slurry.

^c Mean values; the values in parentheses are coefficients of variation.

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Table 8. SUMMARY OF CARBON AND ENERGY BALANCES

	Accounted For			
	Feed Carbon %		Feed Energy, %	
Run 1M-B	99.5, ^a	102 ^b	105, ^a	107 ^b
Run 2M-B	98.3, ^a	100 ^b	104, ^a	106 ^b
Run 1M-9	80.8, ^a	87.0 ^b	85.7, ^a	91.9 ^b

^a Calculated from experimental determinations for moisture, volatile solids, ash, carbon, and heating values of feed and digested solids, and yield and composition of product gas. Volatile solids in digested solids calculated from percent volatile solids reduction.

^b Calculated from parameters in footnote "a" except that ash in digested solids estimated by assuming original ash in feed is in digested solids, that NaOH used for pH control is converted to NaHCO₃ on ashing at 550°C and remains in ash, and that NH₄Cl, if added, is volatilized on ashing.

Table 9. COMPARISON OF FEED AND DIGESTER EFFLUENT SLURRIES

Reactor	Mississippi Hyacinth Slurry	Run 1M-B	Run 1M-4	Florida Hyacinth Slurry	Run 1M-8
Total Alkalinity, mg/l as CaCO ₃	425	3,400	3,460	1,443	2,300
pH	5.01	7.05	7.02	6.10	6.57
Bicarbonate Alkalinity, mg/l as CaCO ₃	302	3,390	3,430	556	2,290
Conductivity, μ mho/cm	3,500	5,620	9,870	2,100	2,680
Volatile Acids, mg/l as HOAc	173	27	26	1,065	5
Chemical Oxygen Demand, mg/l	15,860	12,020	--	17,479	14,630
Ammonia N, mg/l as N	28	27	640	9	2

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Table 10. VACUUM FILTRATION CHARACTERISTICS OF DIGESTION EFFLUENT
(Run 1M-B)

Effluent		Cake		Yield ^a		Conditioned ^b
TS, wt %	VS, wt % of TS	TS, wt %	VS, wt % of TS	Dry Cake, lb/ft ² -hr	Filtrate, lb/lb dry cake	
1.63	60.7	11.5	82.1	1.75	136	No
1.60	61.3	14.4	73.5	0.445	420	Yes

^a 30 sec cycle time, 6 sec form time, 12 sec drying time, 12 sec removal time, 20 in. Hg.

^b Flocculent doses were FeCl₃, 5 wt % TS; Ca(OH)₂, 10 wt % TS.

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Table 11. COMPARISON OF DRY FEED AND DIGESTED SOLIDS

	Mississippi Hyacinth	Run 1M-B	Run 2M-B	Florida Hyacinth	Run 1M-9
Ultimate Analysis, wt %					
C	41.1	31.7	31.3	40.3	27.3
H	5.29	3.82	3.78	4.60	3.30
N	1.96	1.98	1.98	1.51	--
Proximate Analysis, wt %					
Moisture	95.3	--	--	94.5	--
Volatile Matter	77.7	60.7	60.7	80.4	69.4
Ash	22.4	39.3	39.3	19.6	30.6
Heating Value					
Btu/dry lb	6,886	5,280	5,249	6,389	4,391
Btu/lb (MAP)	8,862	8,698	8,647	7,947	6,327
Btu/lb C	16,754	16,656	16,770	15,854	16,084

^a The dry digested solids were prepared by evaporation of the total effluent to dryness on a steam bath, pulverization, and drying in an evacuated desiccator to a constant weight.

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Table 12. COMPARISON OF STEADY-STATE METHANE YIELDS AND EFFICIENCIES UNDER STANDARD HIGH-RATE CONDITIONS^a

	Coastal Bermuda Grass ^b	Kentucky Bluegrass	Giant Brown Kelp	Mississippi Water Hyacinth ^c	Primary Sludge
Methane Yield, SCF/lb VS added	3.51	2.54	3.87	3.13	5.3
Volatile Solids Reduction, %	37.5	25.1	43.7	29.8	41.5
Energy Recovered as Methane, %	41.2	27.6	49.1	35.7	46.2

^a Loadings of about 0.1 lb VS/ft³-day, detention time of 12 days, 35°C.

^b Supplemented with added nitrogen.

^c Run 2M-B.

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